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Andras Kuthi, Helio Zwi, Alfred Y. Wong

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EXPERIMENTAL STUDY OF PLASMOID FORMATION AND TRANSPORT BY MEANS OF MOVING MAGNETIC FIELDS

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Final Technical Report

September 1986 - December 1987

Andras Kuthi, Helio Zwi and Alfred Y. Wong
University of California, Los Angeles, CA 90024

ABSTRACT

Driven, steady-state, stable plasmoids have been generated in an external axial magnetic field by rotating magnetic fields. The plasma equilibrium was stable for any value of beta between zero and unity. The plasmoid was free-standing, well removed from the RF antenna and the limiters. Limits to plasmoid stability have been investigated, and it was found that the antenna near-fields can effectively stabilize gross Magneto-Hydrodynamic modes through the RF ponderomotive force when the rotating field strength was higher than the value necessary for full field penetration. Decay of the driven diamagnetic current and thus the plasmoid has been investigated and it was found, that the resistive current decay was responsible for an induced azimuthal electric field producing the rapid, ion inertia limited E x B radial expansion.

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I. Introduction

Research on self-contained, long-lived plasma entities, so called plasmoids, have been carried out for some time under the name of compact toroid confinement systems within the realm of magnetic fusion. The Spheromak[1], field-reversed mirror[2], field-reversed theta-pinch[3], and the Rotamak[4] represent different approaches to the problem of generation of plasmoids partially confined by their internal currents. The problem of plasmoid generation is intimately connected to the theory of magnetic field generation in conducting fluids[5], the so-called dynamo theory, and to the theory of plasma vortices[6].

A plasmoid represents a concentration of energy partly within the electromagnetic fields confining the plasma and partly the kinetic energy of the plasma itself. The understanding of the physics involved in the formation and transport of plasmoids is of interest to the problem of energy transport to remote targets.

In our research effort we have investigated the fundamental physics involved in a specific approach to plasmoid formation, the method of current generation in plasmas by rotating magnetic fields[7]. This study complements the investigations on plasmoid formation and acceleration based upon Alfven's original work[8] using coaxial magnetized plasma guns and the work carried out in the late 1970's in Los Alamos National Laboratory on the inductive formation and "sligshot" acceleration based on magnetic field-line reconnection[9,10].

The research objective and the main experimental questions to be addressed by us were the following:

1. Determine limitations on plasma parameters in the plasmoid formation process using rotating magnetic fields;

2. Determine physical mechanisms responsible for decay of the plasmoid in the absence of external drive;

3. Determine effect of rotation on plasmoid stability and lifetime;

4. Determine feasibility of travelling EM-wave acceleration;

5. Determine how a moving plasmoid interacts with ambient neutral gas and external magnetic fields.

This set of objectives represented a three year research effort. The present program was terminated after the first year, and thus only experiments on the formation and subsequent decay of the plasmoids, objectives 1. and 2., could be carried out.

In the course of these experiments driven, steady-state, stable plasmoids have succesfully been generated in an external axial magnetic field by rotating magnetic fields[11]. The resulting plasma equilibrium was stable for any value of beta between zero and unity. The plasmoid was free-standing, well removed from the RF antenna and the limiters. Limits to plasmoid stability have been investigated, and it was found that the antenna near-fields can effectively stabilize gross Magneto-Hydrodynamic modes through the RF ponderomotive force when the rotating field strength was higher than the value necessary for full field penetration[12]. Decay of the driven diamagnetic current and thus the plasmoid has been investigated and it was found, that the resistive current decay was responsible for an induced azimuthal electric field producing the rapid, ion inertia limited E x B radial expansion[13].

II. Theory of plasma equilibrium driven by rotating magnetic fields

Consider a circularly polarized cylindrical waveguide resonator mode TM_{010} having an azimuthal phase velocity of $v_{ph} = r\omega$. This rotating magnetic field upon interaction with the plasma transfers not only energy but also angular momentum to the electron fluid and thereby drives a strong azimuthal (poloidal) cross-field plasma current. In equilibrium this current becomes the diamagnetic current which together with the axial magnetic field balances the pressure gradient force

$$dp/dr = J_\theta B_z \qquad (1)$$

The main effect of the RF field is that it forces the form of the diamagnetic current to be that of a rigidly rotating electron fluid co-moving with the wave

$$J_\theta = q n_e v_{ph}. \qquad (2)$$

Using Maxwell's equation connecting the magnetic field with the current density

$$dB_z/dr = -\mu_o J_\theta \qquad (3)$$

together with relations (1) and (2) and assuming that the electron temperature, T_e, is constant and much larger than the ion temperature the self-consistent magnetic field profile and the pressure profile are easily derived:

$$B_z(r) = B_a \tanh[(r/R)^2-C] \qquad (4)$$

$$\beta(r) = b(2-b), \qquad (5)$$

where the constant C is related to the magnetic field on axis, the local pressure is normalized to the pressure of the vacuum magnetic field, $\beta = 2\mu_0 n_e q T_e / B_a^2$, and b denotes the measured diamagnetism normalized to the applied axial vacuum field, $b = (B_a - B_z)/B_a$. The characteristic radius of the density profile is then given by

$$R^2 = 2T_e / fB_a. \quad (6)$$

Although the full range of b runs from 0 to 2, b > 1 corresponding to field-reversal, our experiments were restricted to b < 1. The above relations were first derived by Blevin and Thonemann[7] in a different form.

III. Experimental apparatus

The experiments were performed in one straight section of the RACETRACK device[14] at UCLA. This device, shown in Fig.1, consists of two parallel straight mirrors connected at the ends by two half-toroidal sections. The RACETRACK magnetic field is steady-state, and variable from B_a = 0 to 200 G in the straight sections. The magnetic field strength in the toroidal sections is a factor six higher, and this mirror ratio is kept constant for all values of the applied magnetic field. One of the straight sections contains a hot tungsten filament which is used to generate an electron beam, 0.5 A at -65 V bias, and this beam creates a weakly ionized plasma along its path all around the machine. This toroidal configuration makes it possible to operate at relatively low neutral gas pressure as the ionizing electron population is recirculated. The other straight section houses the high power RF antenna. This antenna is shaped as the stator winding of a polyphase induction motor producing a transverse dipole magnetic field of up to 7 G strength rotating in the electron diamagnetic sense with 486 kHz frequency (Fig.2). Hydrogen is continually bled through the system maintaining a filling pressure of 3.6×10^{-4} torr. Base pressure is kept below 10^{-6} torr. Cylindrical double Langmuir probes (6 mm long 5 mil tungsten wires, separated by 2 mm) measure the plasma density and electron temperature (Fig.3). A set of small electrostatically shielded magnetic loop probes, (1 cm diameter, 20 turns), are used to measure the magnetic field components at three different axial locations (Fig.4). The magnetic field measurements were cross-checked with a Hall effect probe. All probes can be scanned in the radial direction. RF power of up to 2 x 50 kW is pulsed on for 1 - 50 ms at 5 - 15 Hz repetition rate in order to limit the heat deposited in the antenna. Signals are recorded by a digital oscilloscope for single shot wieving and ten shot averages are stored for analysis.

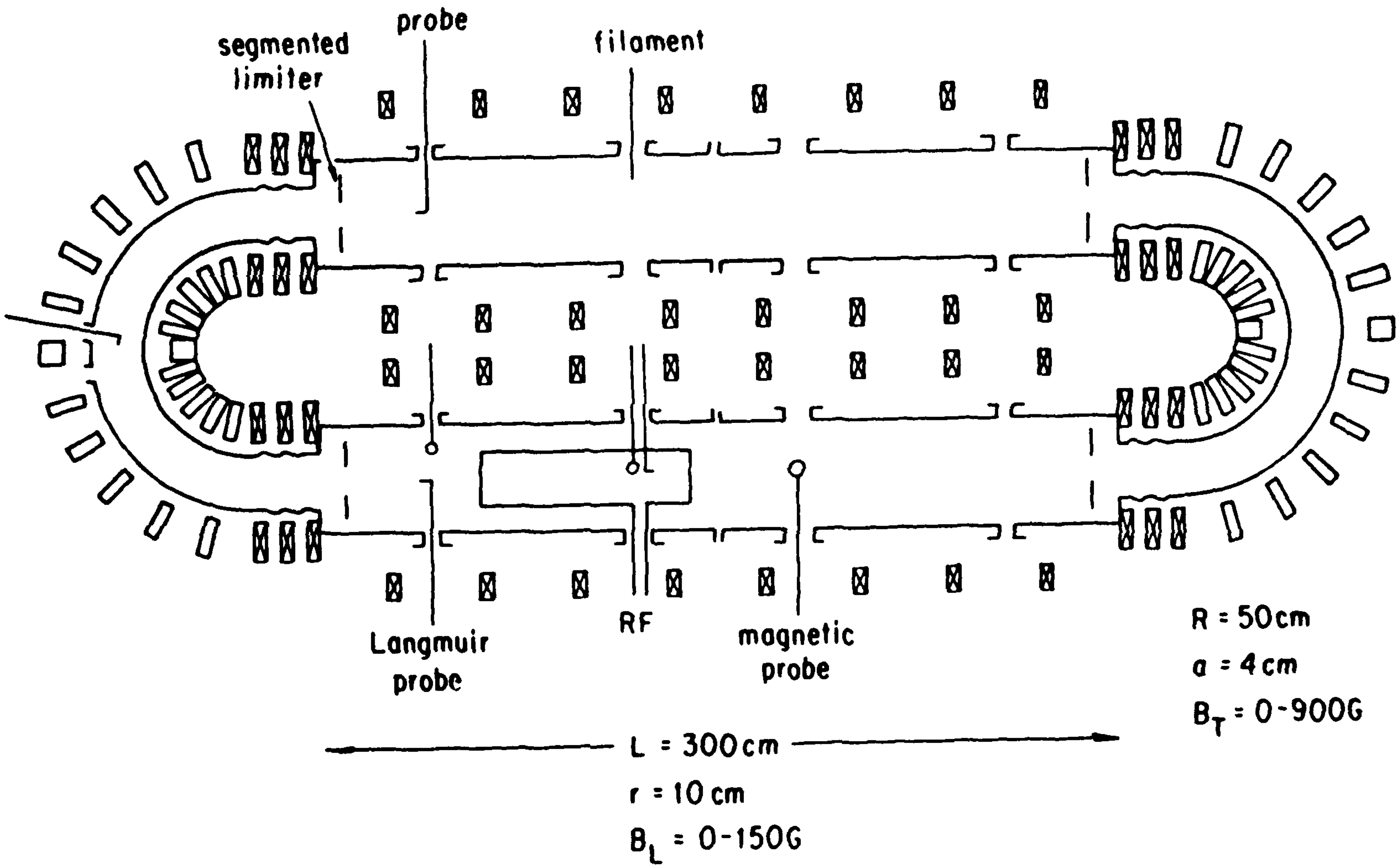


Fig.1. Schematic of the Racetrack Device

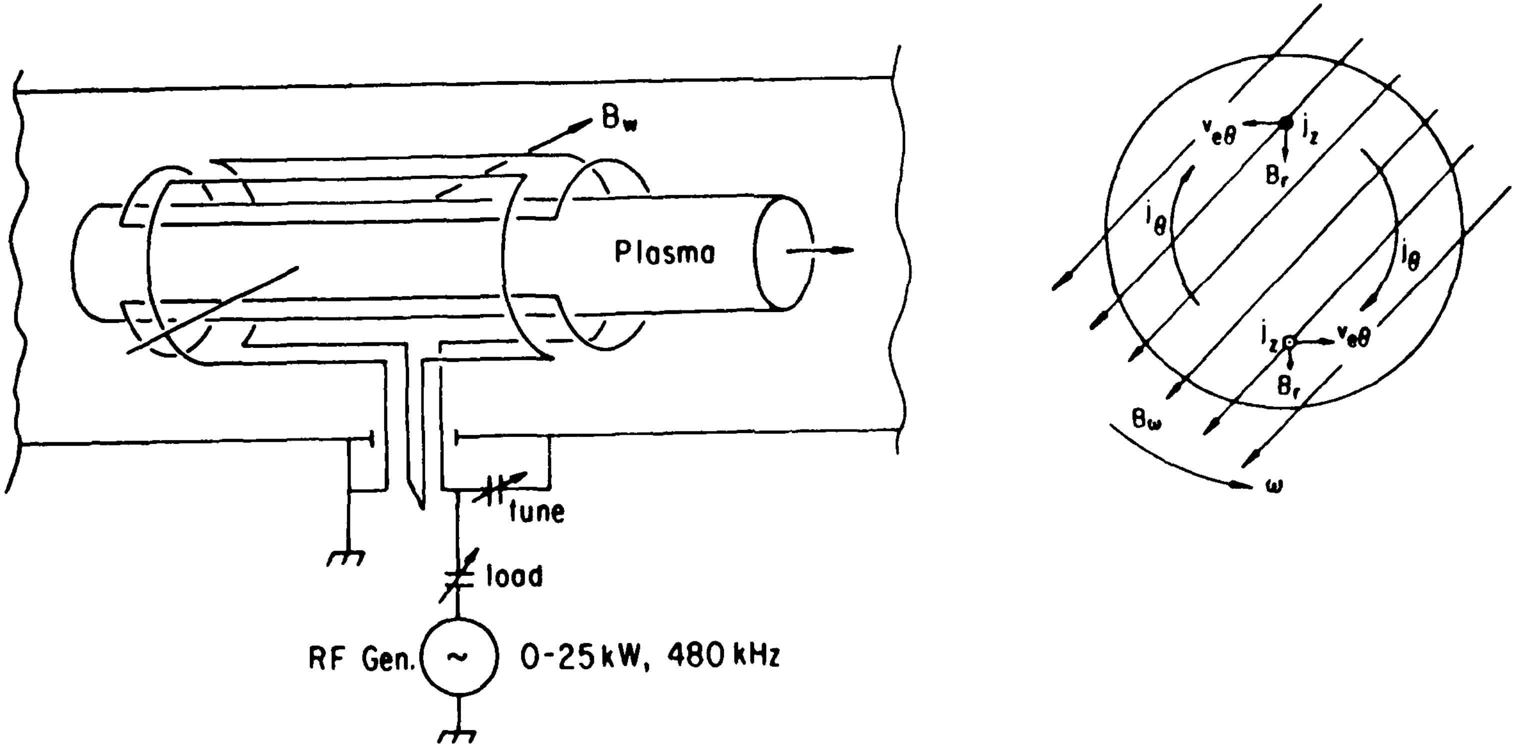


Fig.2. RF antenna circuit and induced plasma currents

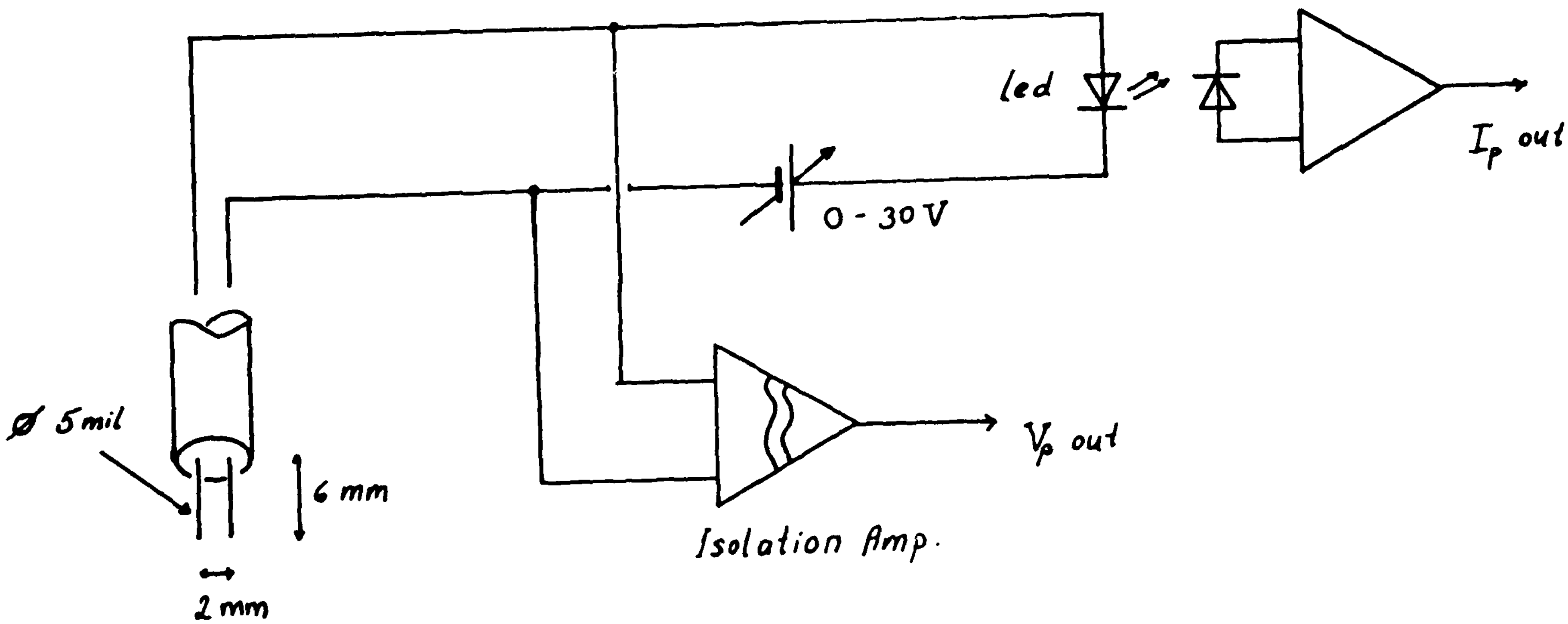


Fig.3. Optically isolated double probe circuit

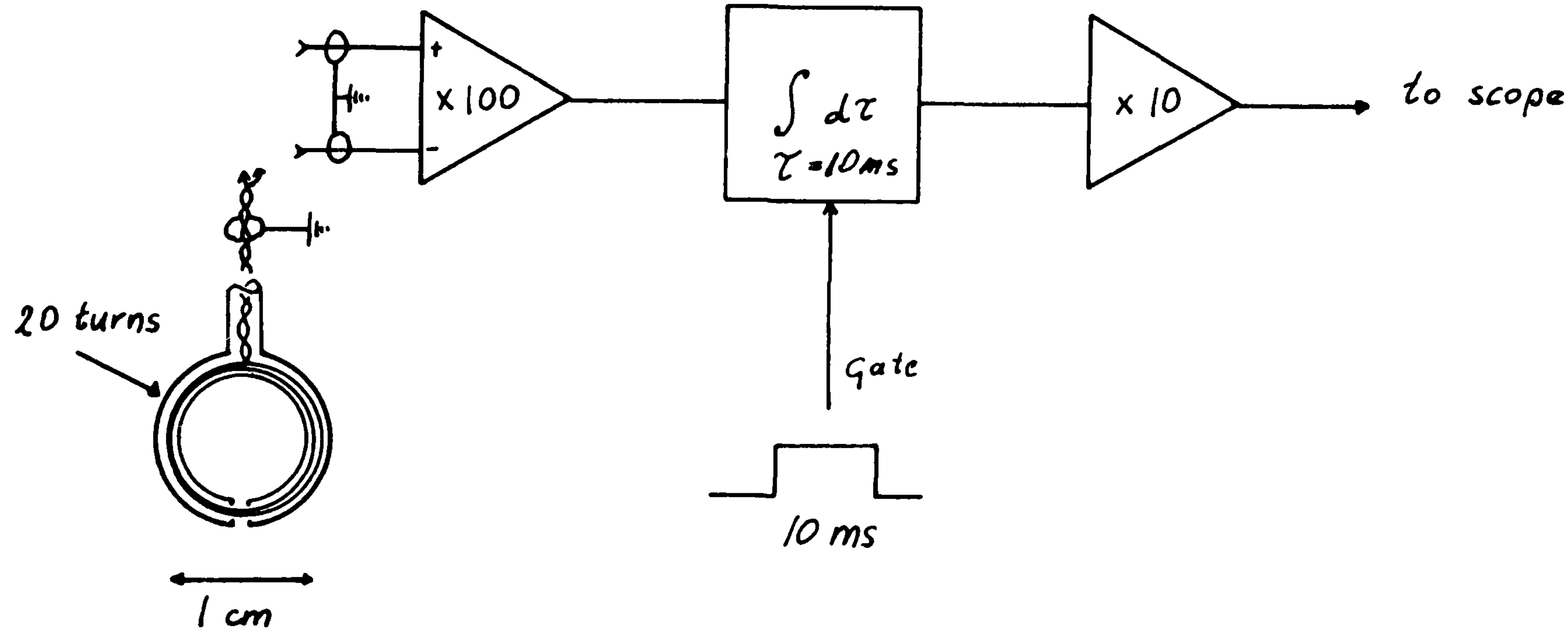


Fig.4. Magnetic loop probe and circuit

IV. Experimental results

During the RF pulse an axisymmetric plasma equilibrium is created. A typical single-pulse diamagnetic signal is shown in Fig.5. The magnetic probe for this shot is at the plasma axis at the midplane of the antennna. The plasma pressure rises to its maximum value in 0.25 ms and it remains constant during the RF pulse. Pulse lengths of up to 50 ms have been tried, and the plasma was found to be stationary after the initial 1 ms. There is no evidence of large-scale fluctuation or instability. The plasma diamagnetic current decays in 0.02 ms. Radial profile of the axial magnetic field and the calculated diamagnetic current density is presented in Fig.6a, while the corresponding pressure profile is shown in Fig.6b. As can be seen, there is excellent agreement between the theoretical and the measured profiles. The plasma radius is approximately 3.5 cm for this particular value of beta on axis, thus the plasma is well removed from the limiters (at 10 cm radius) and from the antenna (at 12.5 cm radius). The high-beta plasma core extends about 20 cm beyond the antenna along the axis, so the plasmoid resembles a cigar shaped plasma "balloon" digging its own diamagnetic well. The peak pressure agrees with the independently measured plasma density and temperature, $n_e = 3 \times 10^{12}$ cm^{-3} and $T_e = 3.4$ eV. These measurements verify the simple form of the pressure balance, eq.(1), without centrifugal or collisional terms. The ion temperature has not been measured, but experience with similar plasmas suggests a value less than the electron temperature, perhaps as low as 0.5 eV. Thus, the ion larmor radius is larger than the plasma size and the ions are confined mainly by ambipolar fields.

Reducing the RF power level results in lower diamagnetic currents and lower plasma beta. When the strength of the rotating field is reduced below a critical value (in these experiments this critical value is about 3 G) coherent low frequency oscillations appear on the diagnostics signals. Further reduction of input power results in loss of equilibrium and stability. The transition form stable to unstable behaviour is shown in Fig.7. The critical rotating magnetic field corresponds to the field strength at which the electrons become magnetized in the wave-field. Thus, for fields larger than the critical field the conditions for electron fluid entrainment by the wave is satisfied: the angular frequency of rotation lies between the electron and ion cyclotron frequencies and the electron collision frequency is smaller than the electron cyclotron frequency.

The ponderomotive force on the nonresonant electrons is strong enough to provide the observed stability. The energy density of the RF field in vacuum does provide a quadratic radial

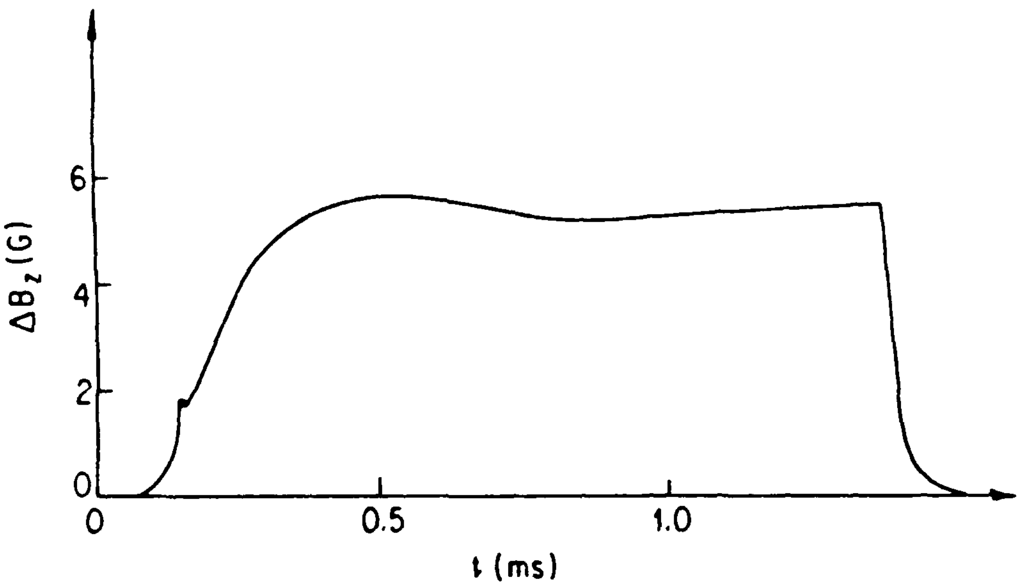


Fig.5. Single pulse diamagnetic signal on axis

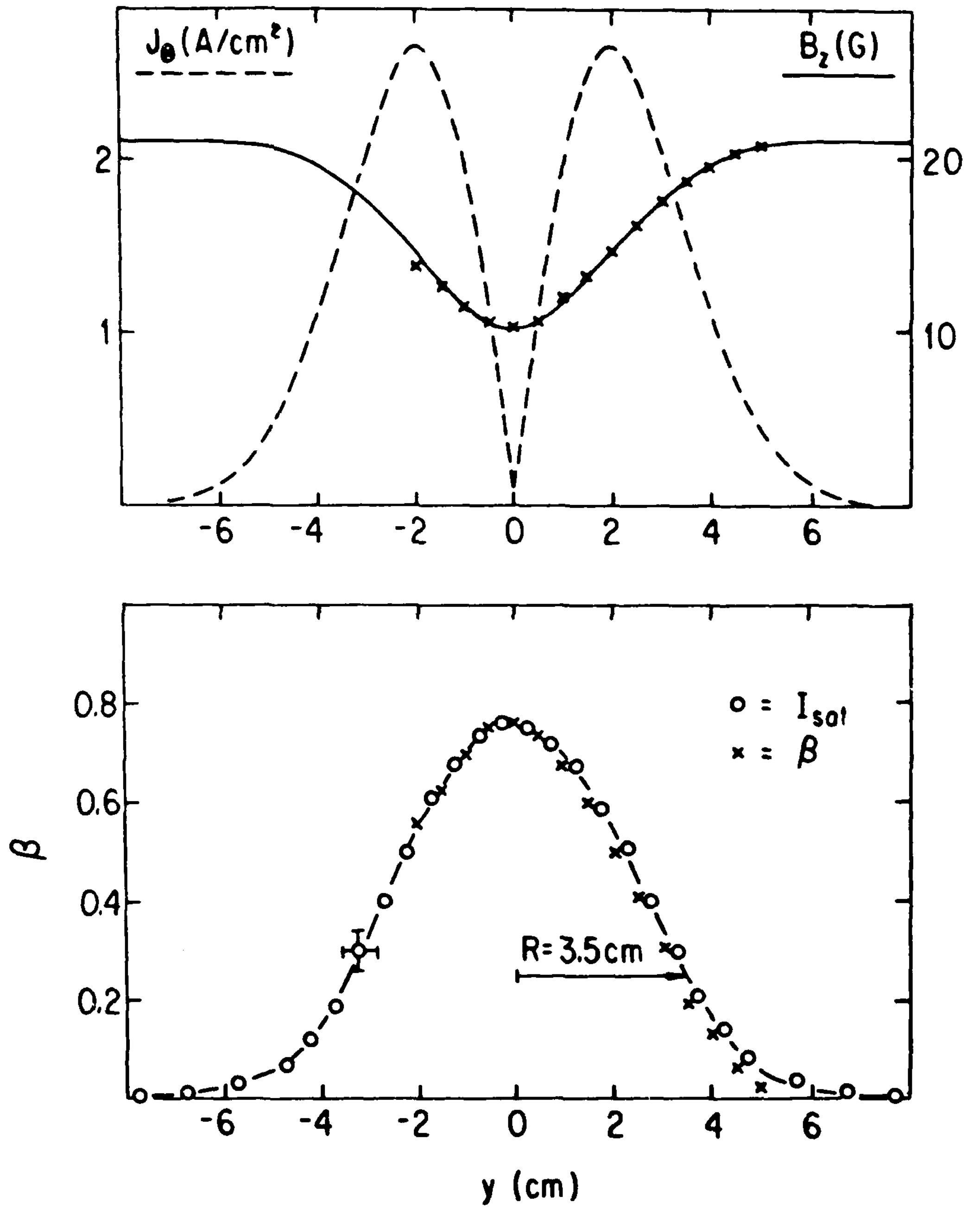
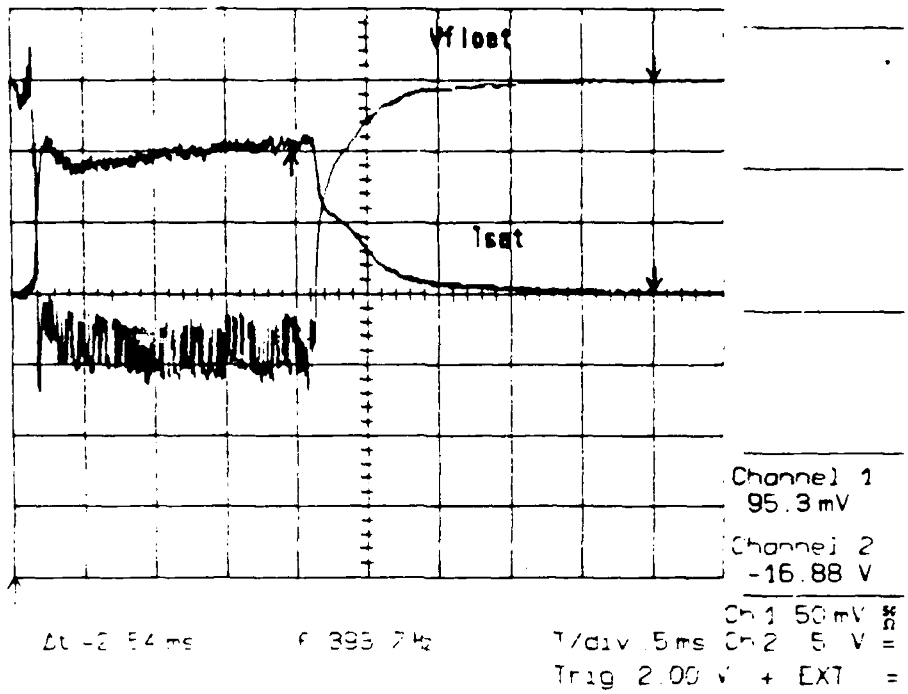


Fig.6. Radial profiles of the self-consistent axial magnetic field and diamagnetic current density; b) Radial pressure profile as derived from magnetic loop (beta) and double probe (I_{sat}) data.

Stable plasma at Bw = 3.0 G



Coherent oscillation at Bw = 2.4 G

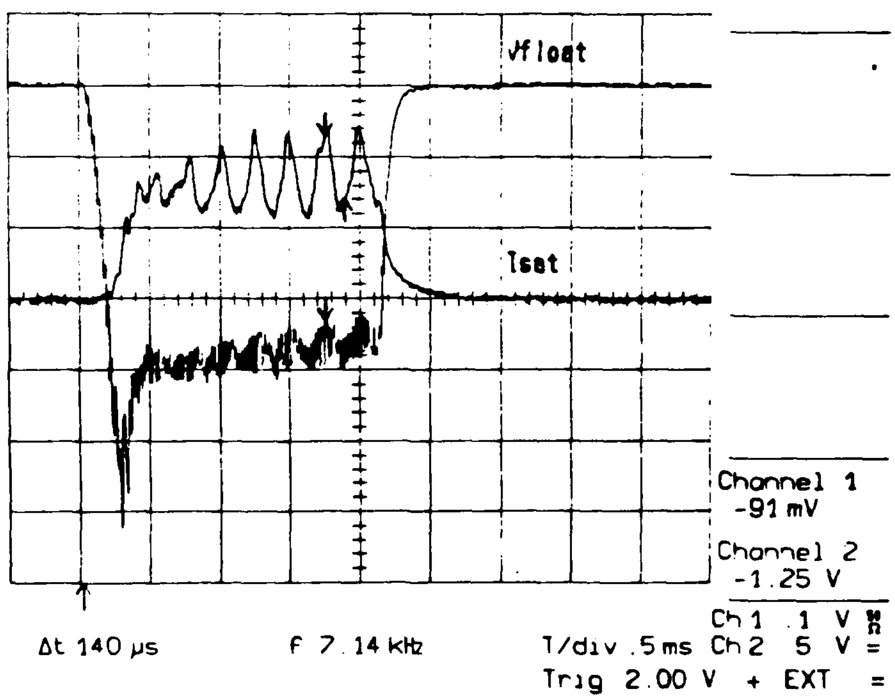


Fig.7. Stable and marginally stable shots showing the transition across the stability boundary as the RF power is reduced.

potential well due to the radial dependence of the induced electric field, $E_z = r\omega B_w$. We have observed negligible screening of the antenna fields by the plasma. In any case, screening changes only the shape of the ponderomotive potential well but not its depth. At high beta the configuration is of the axisymmetric minimum-B type and thus it is stable for all but the rigid displacement ballooning mode[15]. Although the local larmor radius is definitely large, this does not lead to stabilization of the m = 1 mode as evidenced by the instability appearing at reduced RF drive levels. Higher order modes in a low beta plasma can be stabilized by the finite larmor radius effect as well.

Stable equilibrium is observed for any value of beta up to one. Scanning beta is done by scanning the applied vacuum magnetic field. On axis value of beta scales with the applied field as $\beta \propto B_a^{-3}$ for most of the range, suggesting a density scaling as $n_e \propto B_a^{-1}$ (Fig.8). This scaling is not yet understood. Less than 10 kW of RF power is needed to drive 1.7 kA of diamagnetic current at beta = 1, showing the remarkably high efficiency of the rotating field current drive.

Examination of the plasmoid decay in detail, Fig.9, shows that the plasma core is rapidly expanding radially after the RF drive is turned off. The speed of expansion is comparable to the ion sound speed, so the expansion is inertia limited. As the diamagnetic current decays due to electron momentum loss collisions, (this speed is compatible with the calculated Spitzer resistivity) an induced azimuthal electric field appears, $E_i = L_p(dI_p/dt)$, and the plasma is driven radially outward with the resulting $E_i \times B_a$ speed. At higher magnetic fields this expansion speed becomes slower than the m = 1 instability growth time due to the disappearance of the ponderomotive well, and the plasmoid then decays by a combined spiralling and radially expanding motion.

V. Summary of Status of the Research Effort

Driven, steady-state, stable plasmoids have been generated in an external axial magnetic field by rotating magnetic fields. The plasma equilibrium was stable for any value of beta between zero and unity. The plasmoid was free-standing, well removed from the RF antenna and the limiters. Limits to plasmoid stability have been investigated, and it was found that the antenna near-fields can effectively stabilize gross Magneto-Hydrodynamic modes through the RF ponderomotive force when the rotating field strength was higher than the value necessary for full field penetration. Decay of the driven diamagnetic current and thus the plasmoid has been investigated and it was found, that the resistive current decay was responsible for an induced azimuthal electric field producing the rapid, ion inertia limited E x B radial expansion.

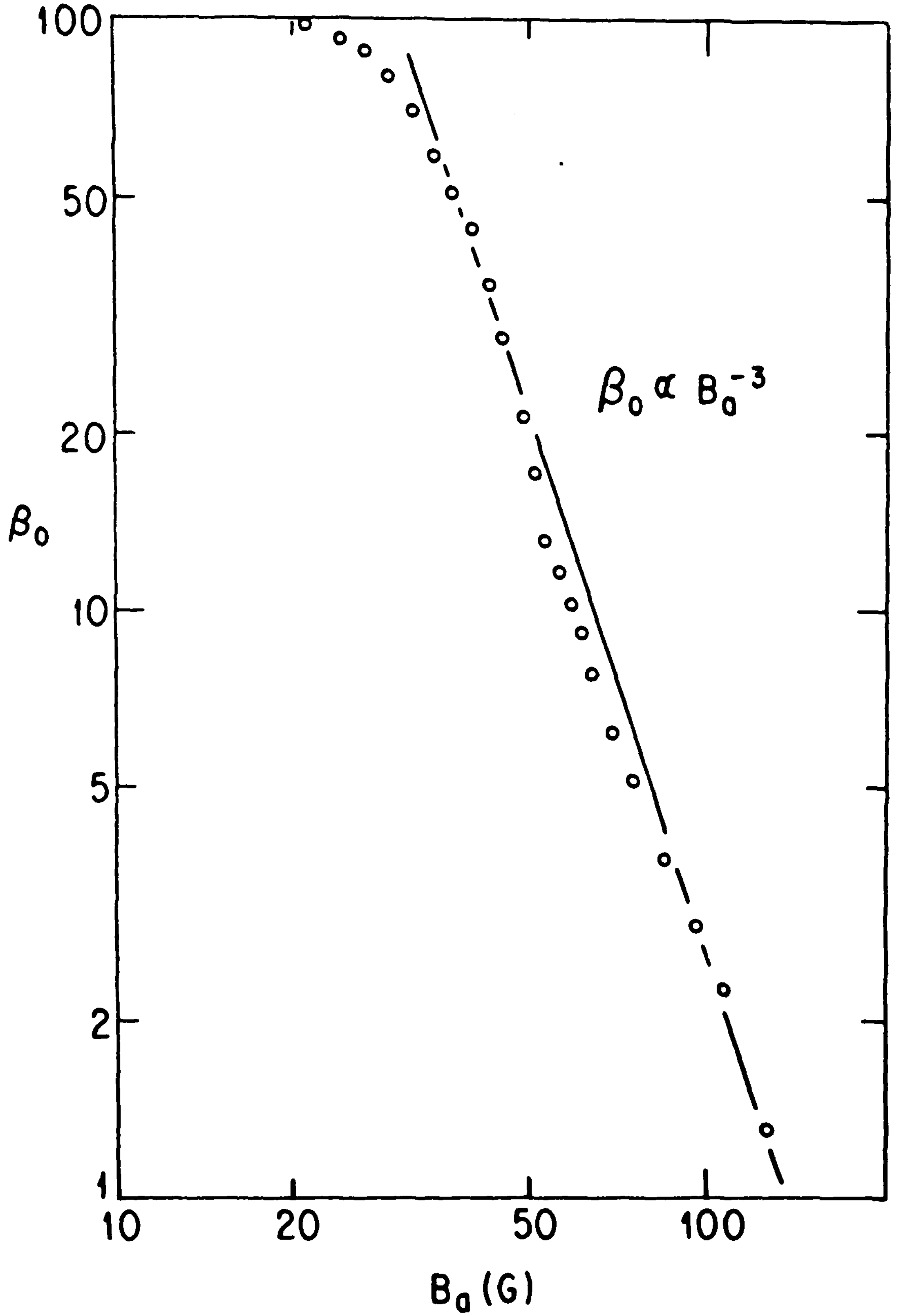


Fig.8. Scaling of on-axis beta with the applied vacuum magnetic field.

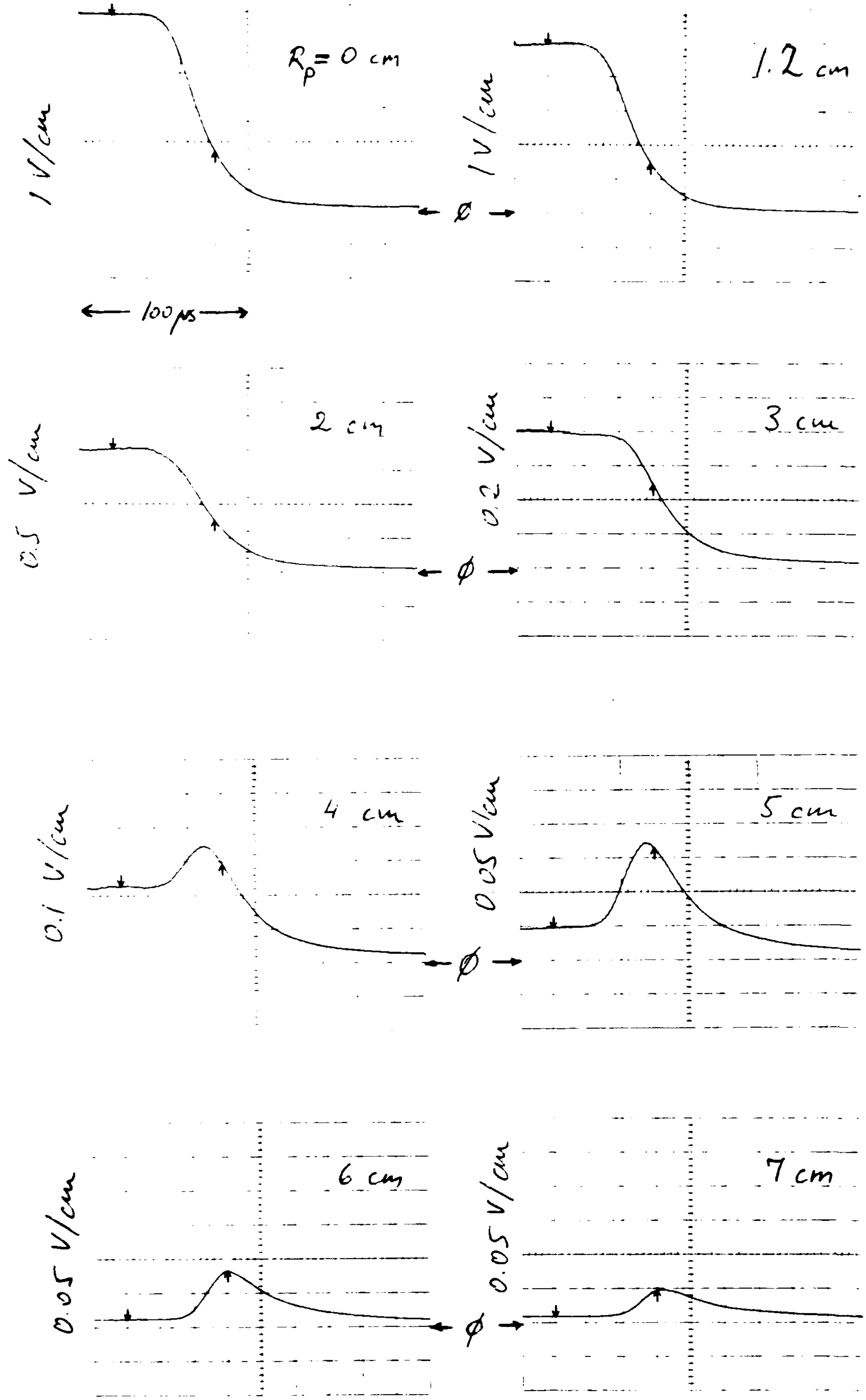


Fig.9. Decay of the plasmoid as recorded by a radially scanned double probe.

The present research effort achieved succesfully the objectives set forth for the first year of the program. We have demonstrated the generation of plasmoids by the rotating field method and investigated the stability and decay processes associated with the high-beta free-standing plasma equilibrium.

The program resulted in the following publications:

1. "Observation of Stable Axisymmetric Mirror Equilibrium at Arbitrary Beta" by A. Kuthi, H. Zwi and A.Y. Wong, UCLA PPG 1078, June 1987, submitted to Phys. Rev. Letters;

2. "Stability of a Rotating Field Generated Mirror Equilibrium" by A. Kuthi, UCLA PPG 1079, July 1987, accepted for Physics Letters A.;

3. "Resistive Decay of a High-beta Plasma Equilibrium" by A. Kuthi and H. Zwi, in preparation for Physics of Fluids.

Professional personnel associated with the research effort:

Dr. Andras Kuthi, Research Physicist, co-principal investigator,
Dr. Alfred Y. Wong, Professor, co-principal investigator,
Mr. Helio Zwi, Research assistant.

Papers presented at the 29th Annual Meeting of the American Physical Society, Division of Plasma Physics, San Diego, CA:

1. "Measurements of RF Fields by Electron Beams in Racetrack" by H. Zwi, A. Kuthi, L. Schmitz and A.Y. Wong, Bull. Am. Phys. Soc., 32 (1987) paper 3W25.

2. "Observation of Stable Axisymmetric Mirror Equilibrium at Arbitrary Beta" by A. Kuthi, H. Zwi, L. Schmitz and A.Y. Wong, Bull. Am. Phys. Soc., 32 (1987) paper 3W26.

Potential Applications and Suggestions for Further Research:

The characteristics of this plasmoid generation method and the plasma parameters achieved make this scheme well suited to several other potential applications. As a method of plasma generation for particle beam sources it offers the advantage of elimination of electrodes and associated problems, and the elimination of plasma-wall contact and the associated particle and energy losses and wall erosion. These very same characteristics make this source attractive for advanced propulsion systems as it may offer higher efficiency than presently used ion engine plasma sources. In its own right, the plasma physics associated with such stable high-beta free-standing equilibrium is important to investigate in more detail. In nature, the earth' and planetary magnetospheres contain such high-beta plasmas and their understanding can be facilitated with laboratory experiments based on our results.

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